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# EFFECT OF POSITIVE PULSE CHARGE WAVEFORMS ON THE ENERGY

## EFFICIENCY OF LEAD-ACID TRACTION CELLS

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### ABSTRACT

The effects of four different charge methods on the energy conversion efficiency of 300 ampere-hour lead-acid traction cells were investigated. Three of the methods were positive pulse charge waveforms; the fourth, a constant current method, was used as a baseline of comparison. The positive pulse charge waveforms were; 120 Hz full wave rectified sinusoidal (FWSR), 120 Hz silicon controlled rectified (SCR); and 1 kHz square wave (SW). The constant current charger was set at the time average pulse current of each pulse waveform, which was 150 amperes. The energy efficiency does not include charger losses.

The lead-acid traction cells were charged to 70% of rated ampere-hour capacity in each case. The results of charging the cells using the three different pulse charge waveforms indicate there was no significant difference in energy conversion efficiency when compared to constant current charging at the time average pulse current value.

### INTRODUCTION

Charging methods could effect battery energy conversion efficiency, and should be a consideration in evaluating possible applications of secondary batteries. The energy conversion efficiency, for instance, of traction batteries for an electric vehicle is a parameter which could impact vehicle operating cost. Various methods of charging batteries have been proposed and reviewed. (1, 2, 3, 4, 5, 6, 7, 8). However, only limited information about the effect of these charging methods on the energy conversion efficiency of secondary batteries exists. Some authors indicate that excessive gassing during charge is detrimental to energy conversion efficiency and suggest that charge control should be based on gas evolution. Others suggest that pulse charging could improve battery energy conversion efficiency.

A test program was initiated to expand the data base on the effect of charge methods on battery energy conversion efficiency. This program was sponsored by the U.S. Department of Energy, in response to the need to develop a viable electric vehicle for urban transportation. Four charge methods were selected and their effect on the energy conversion efficiency of 300 Ampere-hour lead acid traction cells was investigated. Three of the charge methods were different positive pulse charge waveforms; 120 Hz full wave rectified sinusoidal (FWSR), 120 Hz silicon controlled rectified (SCR), and 1 kHz square wave (SW). The fourth was a standard constant current method used as a baseline of comparison. These charge methods were considered realistic options for charging electric vehicle batteries. The energy efficiency does not include charger losses.



In this paper, the results of positive pulse charge waveforms on the energy conversion efficiency of 300 ampere-hour lead-acid traction cells are presented and discussed.

## EXPERIMENTAL

### Cell Chargers

The positive pulse chargers and their specifications were: 120 Hz full wave rectified chargers sinusoidal (FWRS), voltage range 0 to 8 Volts (PEAK) current range, 0 to 1000 amperes, adjustable peak to average current and adjustable firing angle; 1 kHz square waveform (SW), voltage range 0 to 8 volts, current range 0 to 1000 amperes adjustable ratio of peak to average current; and adjustable duty cycle; and a constant current charger, voltage range 0 to 8 volts and a current range 0 to 1000 amperes. Representative charge current waveforms, calculated from oscilloscope voltage traces measured across a shunt during charge, are illustrated in figures 1 to 4. Zero charge current occurred when charger power supply voltage equals the cell voltage.

The FWRS charger was selected on the basis of low cost potential relative to a constant voltage charger which requires close voltage regulation (9). Similarly, the FWRS charger would be inexpensive compared to a constant current charger. Simple circuitry should also result in greater reliability, and lighter weight which could be a factor in selecting a charger for on-board electric vehicle use. SCR and constant current chargers were selected as representative of present charge methods. The 1 kHz SW charger was selected because the circuitry was similar to existing electric vehicle chopper controller circuitry, which could be utilized for an on-board charger. The FWRS and SCR chargers were designed and fabricated at the NASA-Lewis Research Center. The 1 kHz and constant current chargers were designed and fabricated by the General Electric Company (10).

## MEASUREMENT AND PROCEDURES

For this set of experiments, the quantities measured and their accuracies were: average charge current ( $\pm 0.3\%$ ), peak charge current ( $\pm 3\%$ ), peak to average charge current ratio ( $\pm 3\%$ ), discharge current ( $\pm 0.3\%$ ), ampere-hours ( $\pm 0.5\%$ ), and cell voltage ( $\pm 0.3\%$ ).

The average charge current was calculated from the average voltage measured with an integrating digital voltmeter across a non-inductive current shunt. The peak charge current was calculated from peak voltage measured across a non-inductive shunt with an oscilloscope. From these values, the peak to average current ratio was calculated. The discharge current was also calculated from the voltage measured across a non-inductive shunt. A current integrator (ampere-hour meter) was used to measure the charge integral (ampere-hours) put into a cell during charge and taken out of a cell during discharge. The cell voltage during charge and discharge was recorded on a strip chart recorder and also monitored using an integrating digital voltmeter.

The coulombic efficiency was obtained as follows. First the cells were charged to 70% of rated ampere-hour capacity. This was followed by a discharge at 100 amperes to a 1.75 volt cutoff at which point the current was reduced to 75 amperes and the discharge resumed. When the cell again reached the 1.75 volt cutoff, the current was reduced to 50 amperes. At the point where the cell voltage dropped to 1.75 volt while at the 50 amp discharge rate, the discharge was terminated and the capacities delivered during the



three segments of the discharge were noted. A typical set of results for a discharge sequence as described here are listed in table 1. Similarly, the total capacity delivered to the cell during the cycle was obtained from the current integrator. Coulombic efficiency was calculated as a ratio of total ampere-hours out of a cell during discharge to the total ampere-hours into the cell during charge.

The energy efficiency was calculated as a ratio of the total energy out of a cell during discharge to the total energy into a cell during charge. The total energy out of a cell during discharge was calculated by summing the product of measured charge integral and average cell voltage at each current level. The average cell voltage was obtained from a strip chart recording of cell voltage as a function of time. A typical energy output determination is shown in table 1. The total energy into a cell during charge was obtained as follows: The power into the cell as a function of time was measured and recorded using a conventional watt meter. From this data, a curve of as a function of time was made, and the integrated value of this curve was the total energy into the cell. The energy efficiency does not take into account the charger losses.

For each charge method, the charge was terminated when the cell was charged to 70% of its rated ampere-hour capacity. This charge termination was selected due to the onset of excessive gassing which could produce an "aging effect" during the duration of the test, masking the influence of charge method on the cell energy efficiency.

## RESULTS AND DISCUSSION

Representative waveforms used in this experiment are illustrated in figures 1-4. The waveforms are substantially different. However, the time average pulse charge current for each waveform was the same (150 amperes, c/a rate). This enabled a comparison of the effectiveness of the four charge waveform methods.

The results of charging 300 ampere-hour lead-acid traction cells, using the four different charge methods, are summarized in table 2. A statistical analysis of the energy efficiency data was performed. Confidence intervals were calculated based on T-test at the 95% confidence level using a pooled standard deviation (11).

Figure 5 summarizes the average cell energy conversion efficiency and confidence intervals for each of the charge methods. The spread in the data indicate no significant difference in the average cell energy conversion efficiency using the 120 Hz FWRS charger, the SCR charger, the 1 kHz SW charger, or the constant current charger. The energy efficiency did not include charger losses.

Results of this investigation suggest that a relatively inexpensive full wave rectified sinusoidal charger could be used to charge 300 ampere-hour lead-acid traction cells with no significant loss in cell energy conversion efficiency when compared to more expensive charge methods. A 1 kHz square wave charger could also be used with no loss in cell energy conversion efficiency and this suggests the possibility of utilizing existing electric vehicle chopper controller circuitry for an on-board charger. Pulse charging, of the type investigated, did not lead to an increase in energy efficiency over that of the constant current charge method.



The effect of pulse charging on the charge/discharge cycle life of 300 ampere-hour lead-acid traction cells is unknown at this time. However, previously reported work (12), using the same charge methods, but small (5 ampere-hour) nickel-zinc cells suggest there may not be as effect on cycle life.

#### CONCLUDING REMARKS

A relatively inexpensive full wave rectified sinusoidal charges could be used to charge 300 ampere-hour lead-acid traction cells with no significant loss in cell energy conversion efficiency when compared to more expensive charge methods. The SCR and 1kHz SW chargers also could be used with no significant loss in cell energy conversion efficiency. The 1kHz charger is a contender for an on board electric vehicle charger because it could utilize existing electric vehicle chopper controller circuitry.

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TABLE I. - CHARGE (AMPERE-HOUR) AND ENERGY (WATT-HOUR) DETERMINATION OF A REPRESENTATIVE 300 AMPERE-HOUR LEAD-ACID TRACTION CELL

Discharge current, amp,	Charge output, amp-hr	Average cell voltage, V	Energy output, watt-hr	Cutoff voltage,* V
100	139.5	1.87	260.9	1.75
75	27.4	1.81	49.6	1.75
50	<u>30.4</u>	1.82	<u>55.3</u>	1.75
	197.3		365.8	

\*Voltage at which discharge was terminated.



TABLE II. - RESULTS OF CHARGING 300 AMPERE-HOUR LEAD-ACID TRACTION CELLS  
USING REPRESENTATIVE WAVEFORMS

Cell	Charge waveform	AH <sub>1</sub> <sup>1</sup>	AH <sub>0</sub> <sup>2</sup>	Coulombic efficiency AH <sub>0</sub> /AH <sub>1</sub> , percent	WH <sub>1</sub> <sup>3</sup>	WH <sub>0</sub> <sup>4</sup>	Energy efficiency WH <sub>0</sub> /WH <sub>1</sub> , percent	Percent charged AJ <sub>1</sub> /300	T <sub>1</sub> <sup>5</sup> (°F)	T <sub>2</sub> <sup>6</sup> (°F)
2	Constant current (fig. 1)	210	204	97	527	381	72	70	--	104
2	120 Hz FWRS (fig. 2)	210	199	95	529	371	70	70	72	100
2	120 Hz SCR (fig. 3)	210	202	96	543	378	70	70	76	111
2	1 kHz SW (fig. 4)	210	194	92	543	363	67	70	73	107
3	Constant current (fig. 1)	210	197	97	525	366	70	70	73	98
3	120 Hz FWRS (fig. 2)	210	200	95	545	372	68	70	73	102
3	120 Hz SCR (fig. 3)	210	199	95	561	370	66	70	--	107
3	1 kHz SW (fig. 4)	210	196	93	544	364	67	70	--	110

1. Total amp-hrs into cell at charge.
2. Total amp-hrs out of cell at discharge.
3. Total watt-hrs into cell at charge.
4. Total watt-hrs out of cell at discharge.
5. Temperature of cell electrolyte at start of charge.
6. Temperature of cell electrolyte at end of charge.

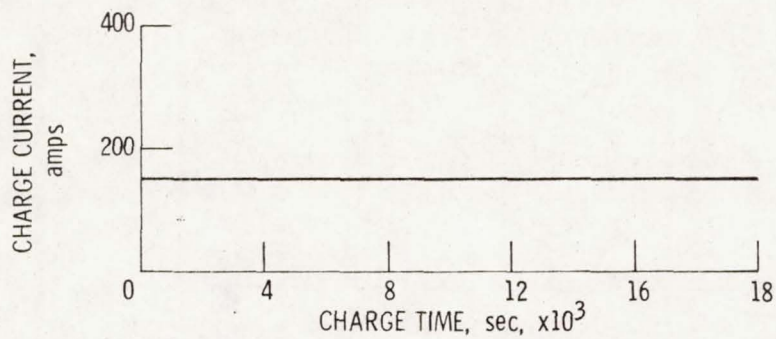


Figure 1. - Charge current as a function of charge time for constant current charger.

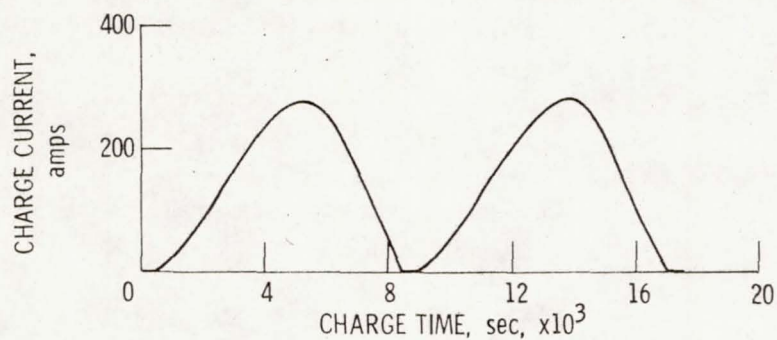


Figure 2. - Charge current as a function of charge time for 120 Hz full wave rectified sinusoidal charger.

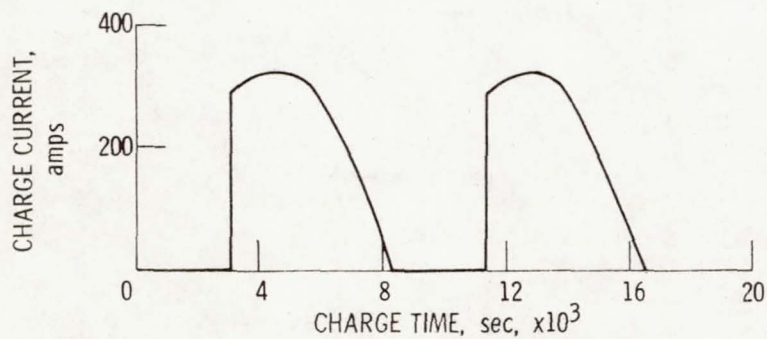


Figure 3. - Charge current as a function of charge time for a 120 Hz silicon controlled rectified charger.



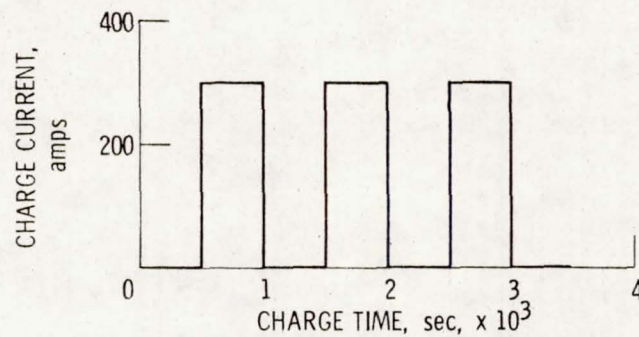


Figure 4. - Charge current as a function of charge time for 1 k Hz square wave charger.

#### CHARGE METHOD

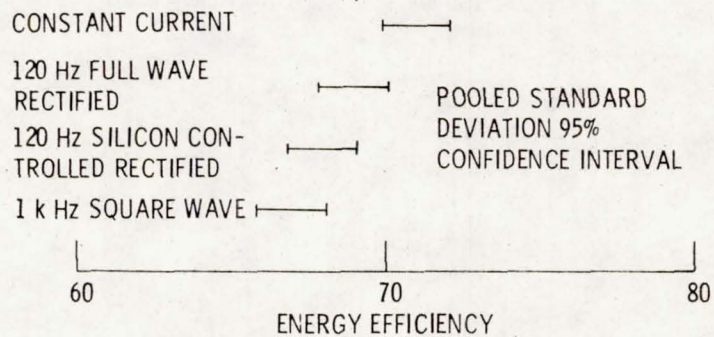


Figure 5. - Average energy efficiency for charge methods.

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